Review:

Application of Micro-Electro-Mechanical Systems (MEMS) as Sensors: A Review

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This paper presents a review of the current applications of Micro-Electro-Mechanical Systems (MEMS) in the robotics and industrial applications. MEMS are widely used as actuators or sensors in numerous respects of our daily life as well as automation lines and industrial applications. Intersection of founding new polymers and composites such as silicon and micro manufacturing technologies performing micro-machining and micro-assembly brings about remarkable growth of application and efficacy of MEMS devices. MEMS indicated huge improvement in size reduction, higher reliability, multi-functionality, customized design, and power usage. Demonstration of various devices and technologies utilized in robotics and industrial applications are illustrated in this article along with the use and the role of silicon in the development of the sensors. Some future trends and its perspectives are also discussed.

Keywords: MEMS, robotic, sensor, actuator, micromachining

1. Introduction

MEMS generally refer to electrical devices fabricated in micrometer range and any moving parts inside are in the range size of μm. Construction of MEMS is followed by advanced technologies like photo-lithography process or such techniques which are used in IC (computer chip) fabrication (CMOS, BICMOS, Bipolar) [1, 2]. In the matter of size, MEMS devices are about 100 μm or 0.1 mm and components inside a device is generally about 20 μm (0.02 mm). Foundation of new materials and accessing fabrication in micro scale enables size reduction of sensors and actuators with lower cost and more precise sensing. Presently micromachining (called as surface or bulk), RIE, LIGA and lithography are the main techniques accessible for MEMS manufacturing and fabrication [3]. Considering the micro size capabilities, MEMS is now compatible to be applied in bio-medical applications, micro-electronics, aerospace, smart materials and etc. MEMS has become the most sought after and best substitution for traditional actuators and sensors, given their low cost manufacturing, small size, high response, low power consumption, customized applications and flexible geometry. In terms of sensor, similar to the traditional types, they provide electrical indicator aspects such as voltage, current, resistance or capacitance to measure the desired sensing magnitude. The main difference is the size, repeatability, reliability and precision of MEMS devices at the same time with the lower price. Pressure, acceleration, optical, infrared or gyroscopes are the primarily used MEMS technologies in the industry. They are very popular in automotive industries, aerospace and smartphones. When MEMS devices are used as actuator, electrical actuation performs any kind of dynamic reaction such as grip, pumps, position, manufacture, valves and etc. [4]. As a sensor, the working principle stays the same that the acting parameter results in elicitation of electrical responses out of sensor for purposes of measurement.

In the market, the total sensor market value reached 10 billion dollars in 2017 with the potential growth up to 21 billion dollars in 2022 only for automotive industries mostly in terms of radar, lidar, self-driven cars, embedded and optical sensors. As regards the medical and health industry implementing MEMS increasingly, the market size is estimated to arrive at 50 billion dollars by 2021 [5–7]. Progressive innovations and technologies such as nanomaterials, nano-particles, nano-wires, nano-porous, silica and many more lead to such highly targeted therapeutics, wireless capsule drugs, mass screening, and early detection of possible diseases. It has been anticipated to revolutionize medical diagnostics as regards visual inspection and propose drug delivery nano robots. A comparison of semiconductor and MEMS actuators and sensors market is presented in **Fig. 1**. Although all semiconductor devices not in the category of MEMS devices but the size and growth of each device type is significant. The highest request is on the RF and CIS (CMOS Image Sen-

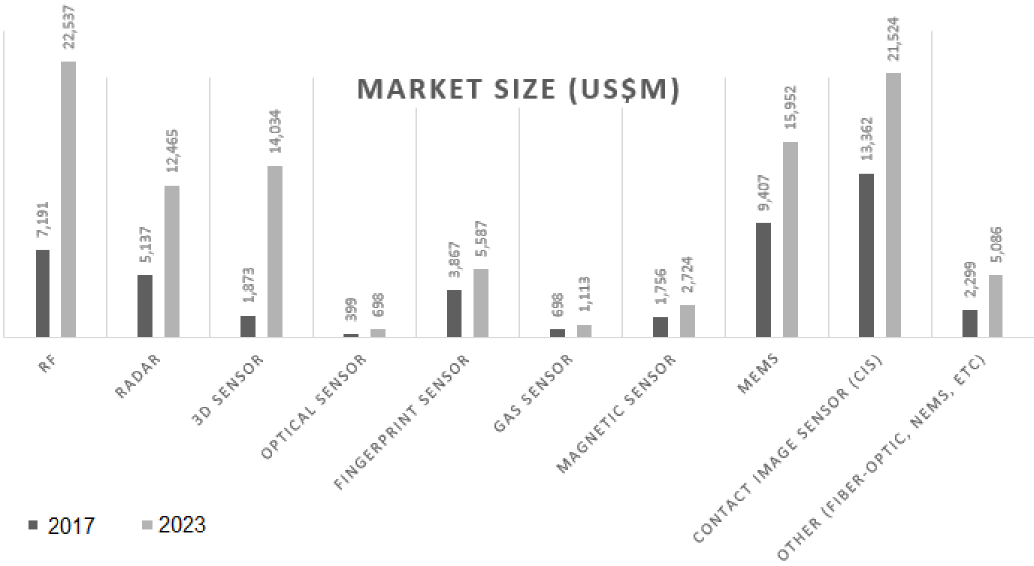

Fig. 1. Semiconductor and MEMS market value comparison for sensors and actuators [7].

sor) devices estimated to exceed 20 billion dollars in 2023 each [8].

2. MEMS Devices

Initial MEMS sensors were first recommended into the market as accelerometer, gyroscope and pressure sensors during 1970 and later as RF (radio frequency) instruments, micro-fluidic, micro pumps, and biomedical equipment [9–11]. The technology of nanomechanical instruments transfigures measurements in micro scale transpositions or performance of micro weight forces, predominantly at the molecular scale [12]. Micro mechanisms located inside MEMS are measuring the required quantity such as accelerometers with mechanisms of measuring momentum or bending structure to identify acceleration. MEMS accelerometers are tiny microstructures inside an accelerator that can bend because of momentum and gravity with precise accuracy. In the industry, there are highly demands to implement and combine hardware and software with the embedded systems to perform specific applications. MEMS devices also help in this application with custom made sensors or actuators with the great potential of designing the performance from scratch. It means that based on what user wants to perform, or the type of parameter user wants to read, various MEMS structures are available or could be fabricated. A unique design is shown in **Fig. 2** representing a dual usage MEMS device that could be worked as actuator or sensor base on the application [a]. Nanotechnology helps in fabrication and delivery smaller, lighter and compressed devices with the name of NENS (Nano-Electro-Mechanical Systems) [13, 14]. MEMS devices may come out of a single crystal structure which is named bulk micro-machining [15, 16]. If the base structure is bulk silicon and used to fabricate on the surface, this type of micromachining is called surface micromachining. In the process of surface micromachining, the MEMS structure is formed based on thin poly-silicon layers that grown on the surface of the single crystal silicon wafer [17].

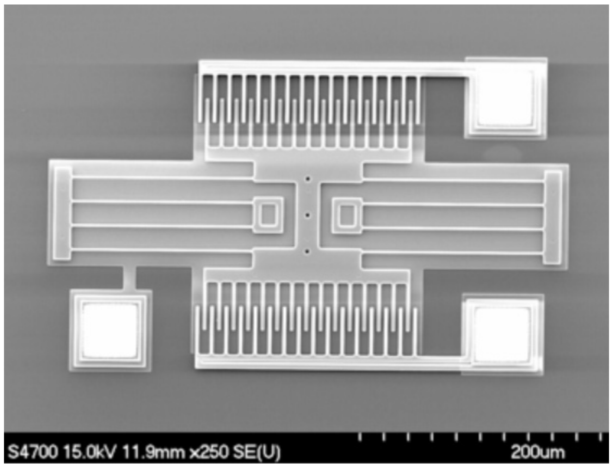

Fig. 2. Dual usage MEMS structure (can act as sensor and actuator) [a].

3. Silicon Role

It is more than four decades of silicon utilization for medical applications including in-vitro and in-vivo applications [18, 19]. Micro-fabrication innovations result in different types and products of silicon with different mechanical and electrical properties. Nano-technology and advanced micro-assembly methods facilitated development of more compact, custom design, cheaper, higher performance devices with different applications [20, 21]. For biomedical applications, using silicon as insulator or

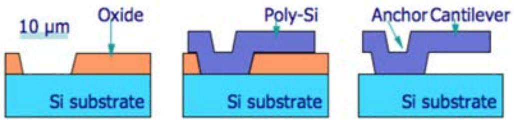

Fig. 3. MEMS fabrication with surface micro-machining [b].

implantable sensors is the edge of technology [22–24]. These sensors were used for fully implantable cochlear prosthesis and, brain sensing technology, comprised of an embedded signal-processing circuit. Silicon traditionally involved creating pathways for electricity within components such as integrated circuits [25]. On the contrary, silicon is transformed by MEMS into mechanically moving parts. In the past decade, this process has become useful in growing number of industries.

Silicon as one of the primary materials of microelectronics plays unique role in expansion and elaboration of MEMS and microstructures ability. In robotics applications, silicon is used in different areas such as soft actuators which they are available in different formations and applications as stated in [23, 26, 27]. They are used as grippers, soft actuators, end-effectors or in exoskeleton devices [27]. Smith (founder of semiconductors) first used the silicon in 1954 notifying the greater piezoelectric effect of this material rather than metal films and strips [28]. With this discovery, silicon could then be utilized not only for electronic devices but also for sensors rather than detected mechanical strain. The silicon material is very cheap with having such properties as highly pure form, strong (approximately 80% as strong as steel), compatible with microelectronics and has excellent piezo-resistivity properties. Other combinations of silicon, such as silicon nitride and silicon dioxide are also used in MEMS devices to form insulation and structured layers or optical windows [29–31]. If the formed layer is thin, it could be composited by other technologies such as sputtering, coating, evaporation, chemical deposition and others. In some sensors or custom design, MEMS devices that need 3D form structure, a single layer is not suitable. To form the multi-layer pattern, more wafers need to be bonded together with some innovative techniques such as fusion bonding, anodic bonding, eutectic bonding, or adhesive bonding [32, 33]. Some progress has been made recently in detection of new materials in the MEMS fabrication such as polymers. They are very beneficial with easy and fast process with many different choices with varying properties. For the micro-fabrication purpose, different techniques of fabrication are running currently on silicon material, and a schematic one is shown in **Fig. 3**. These advance fabrication methods have low costs for batch processing to deal with large quantities. In addition, polymers are the alternative of silicon, because they are considered better choice for rapid prototyping or small-scale manufacturing. Mainly poly-methyl-meth-acrylate (PMMA), and poly-di-methyl-siloxane (PDMS) are the most applicable polymers in the process of MEMS [34]. Reports have also been made of using polyimide materials for MEMS sensors [34]. The PMMA material is available in solid form and thermal casting or molding is used for patterning. Following the process of being molded, proper structural properties that could be used in MEMS devices are demonstrated [35].

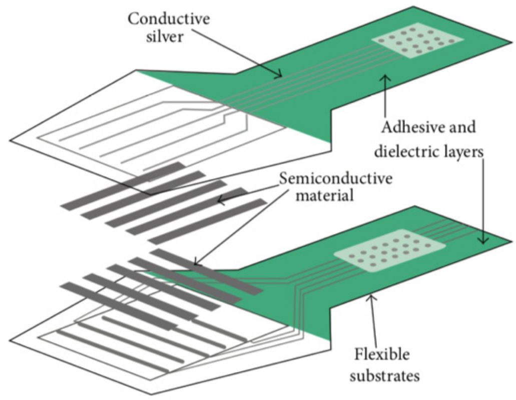

Fig. 4. Tactile sensor schematic description [c].

With the advent of innovations in the field of 3D printing, researchers have started to put emphasis on the development of 3D printed silicon-based sensors for biomedical applications [36]. Fabrication of these sensors is quick and capable of being customized in a wide range, robust in nature and highly durable. One of the substantial issues with these materials is their biocompatibility, especially as regards the sensors used for in-vivo applications. The significance of these 3D sensors drives from their integration with other organic and metallic elements to form sensing prototypes [37].

4. Robotic Applications

4.1. Tactile and Pressure Sensors

One of the most requested applications in the robotics field is the pick and place and gripping mechanism to move and transfer object remotely or autonomously. Tactile sensors will be used for the precise conduction of this process and sense the pressure made on object. The principle of tactile pressure sensor is to measure the physical force between object and sensor surface [38]. Pressure and torque are examples of a prominent parameter that is more often than not measured through physical touch. Detection and measurement of a point contact force can also be considered as a part of touch sensor for pressure and torque. Tactile sensors could be considered as group of touch sensors placed besides each other [39]. Imagine piezo-resistive material sandwiched between two pieces of flexible polyester each half of which has printed silver conductors [40, 41]. The final product with about 0.1 mm thickness could be used as sensor for various applications of industrial and medical robot. A schematic tactile sensor assembly is shown in **Fig. 4**. SMA (Shape Memory Alloy) is also used in actuation of micro-actuators to act as tactile sensor, whose mechanism is discussed in [42]. Because of numerous human machine interfaces (e.g., wheelchair seating systems, driver's seats, hospital beds) and owing to incongruence of human joint, the sensor should be in a wide range of resolutions [43]. When force is applied to the sensor, the sensor that is represented by a variable resistor will be transformed and the possible current will flow through the device. Afterwards, the analogue data collected through the electronics are later on compensated with appropriate calibration [44, c].

In MEMS pressure sensors, the main structure is a flexible diaphragm possible to deform in the presence of a pressure difference and convert this deformation to electrical signal. The simplest structure of pressure sensors is fabricated by bulk micromachining to create the silicon membrane [5]. Around the diaphragm different piezo-resistors are placed to detect such micro vibrations. The whole assembly is bonded to a glass substrate and sealed in the cavity. Any changes or deformation of diaphragm leads to changes of piezo-resistors and their respective resistance [45, 46]. The output resistor changes transmission to voltage signal. This technology becomes more reliable with advance technologies and reaches low-cost production price that make it accessible. The piezo materials are sensitive to temperature and stabilizing temperature should follow to get the more accurate results. Capacitive type pressure sensors are less sensitive to temperature changes but the output signals are weaker. With different variations of pressure sensor available in the market, capacitive pressure sensor is valid in robotics mostly. The compression, extraction, and distance of initial plate capacitor with the nodes are chiefly measured with such sensors. Capacitive tactile pressure sensors are the most sensitive techniques to measure small deflections or displacements [47]. Pressure sensors have been developed by researchers for many years thanks to such features of having high spatial resolution, good frequency response, low power consumption, and a large dynamic range [48]. In fact, application requirements primarily determine the pressure sensor design and structure. Robotics, automotive and medical industries are the main consumers of pressure sensors [49–53]. A wide variety of materials and technologies have been utilized for the pressure sensor, causing performance versus cost trade-offs as is clear from **Fig. 5** with multi layers assembly. A variety of choices for different applications are also arranged for the electrical output signal [54].

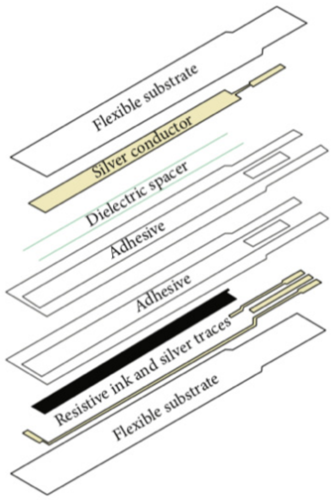

Fig. 5. MEMS flexible force sensor details [c].

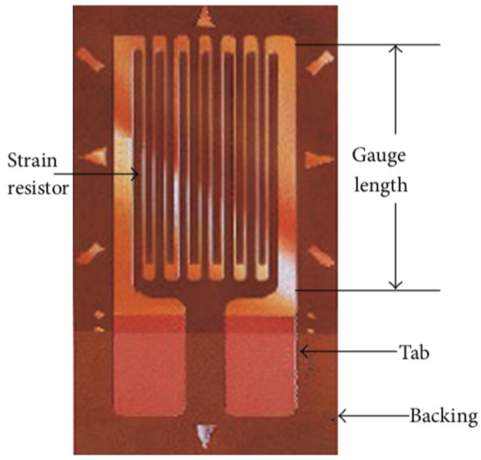

Fig. 6. Strain gauge principles [55].

4.2. Mass and Strain Gauges

In industrial applications, mass force is measured through load cells used as strain gauge or weight sensor. The type of strain gauge is the same as pressure with a different architecture. Load cell sensor might be equipped with robotic arms, end-effectors, and grippers for detection and identification of compression force to control and prevent disorders or damages done to the object (**Fig. 6**). Given the variety of possible applications, load cells are supposedly considered to be of high importance and popular [56]. Traditionally, load cell and mass gauges used steel or aluminium as part of sensing element to measure deformation and total applied force. This metal part is currently replaced by the silicon material that does not have the creep and hysteresis issued like metals. Also piezo-resistive materials are used in mass, strain and force sensors as they have higher sensitivity and scaling with lower noise. There also alternative methods beside strain gauges like piezoelectric elements or variable capacitance technology to measure loads. Given the applied force and types of application, multiple form factors of load cells are available to apply (single or multi axis). Identifying force along two axes by using a capacitive MEMS device to measure force is presented in [57]. Normally multi axes sensors are used in devices to prevent any fault or wrong sensing. A design and procedure of piezo-resistive three-axis force sensor is described in [58]. Strain gages are small patches of silicone or metal for the calculation of mechanical strain and conversion of the load acting to electrical signals. This load cell is considered an analogue type tool utilized to measure weight. When a load is ap-

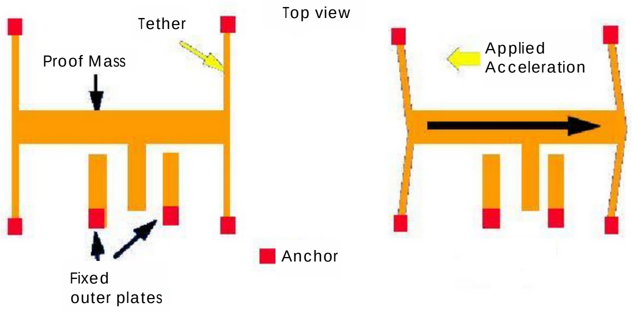

Fig. 7. Accelerometer assembly structure [61].

plied to a stationary object, stress and strain parameters are brought about as a result.

4.3. Accelerometer/Gyroscopes

Accelerometers identifying acceleration of an object are mounted in a direction based on analogue and digital types [59]. They are used in robotics with different areas such as encoders, motors, self-balancing robots, underwater vehicles, airplanes, cameras and others [60]. A schematic assembly of an accelerometer is shown in **Fig. 7**. The human range of measurement allows them to be used in cutting-edge industries such as aerospace and military (autonomous drones, air-defense, missile, weapon, rocket deployment) [26, 62, 63]. So far, major accelerometers types in the market are silicon capacitive, piezo-resistive and thermal accelerometers. The highest share in the market is the silicon capacitive sensors used in automotive industries [64, 65]. Although they were used initially in luxury cars few years ago, but with the aid of cost-effective technologies, mid and low price cars steadily consider them currently. As MEMS is tough working environment, shock resistance products were also developed to measure the parameter of object that is mounted. MEMS accelerometers are tiny microstructures inside an accelerator that could be bent because of momentum and gravity. This displacement is then converted to the electrical quantity. The forces that can cause vibrations which are detected by the accelerometer can be static, dynamic or gravitational. For gravitational, as sensor measured gravity (or shown as $G = -9.81$ m/s^2), they are more sensitive to motion and can be triggered at the slightest changes in gravitational pulls. As every accelerometer is subject to gravity, by measuring this, the robot can detect what angle it is as regards gravity [7]. In aeronautical applications, gyroscopes are one the vital components to detect and measure attitude, speed and rotational rates. An integral part of all aeronautical control systems is used for the attitude and rotational rates for navigation. For the military and security application, gyroscopes are administrated in missile guidance, drones, navigations, GPS tracking and smart munitions [66].

Industrial automation is the other criteria of implementation MEMS components which use benefits of them in terms of reliability, sensitivity, and cost-effective solutions. Remotely powered sensors, autonomous sensors and miniaturized actuators and sensors empower the robotics usage inside automation lines. Infrared sensors, microphones, optical devices and RF communicators are the other types of popular MEMS devices used in automotive, smartphone and robotic industries. Size constrained applications and low energy consumption make these components ideal for remote access and wireless monitoring [67–69]. Possibility of communication and integration between sensors makes a network interlink the stations of automations lines with a cost-effective solution. Mass production and running non-stop lines use this benefit to avoid involving human power and possible mistakes and failures in the process.

5. Future Trends

Application and technologies of MEMS devices in robotics and biomedical reviewed in this paper show the role and impression of MEMS in different fields of application. Currently MEMS devices are enrolled in every electrical component and industrial machine [46, 70]. Performance, efficiency, being inexpensive, and low energy use are the main interesting factors of selecting MEMS devices. With new innovations in materials and fabrication, IoT (Internet of Things), and advanced technologies, MEMS are expected to be more involved in our routine life [71, 72]. **Fig. 8** shows trends and future estimation of MEMS devices in actuators and sensors for year 2023 compared to the data in year 2017. The market value is mostly using RF devices, inertial, pressure sensors, microphones, optical, infrared devices, oscillators. The primary target industry for these sensors are the automotive, aerospace and smartphone industries. Estimation of RF devices market in the near future (with IoT and 5G) proves significant increasing to 15 billion dollars in 2023.

Now it is possible to design and fabricate a custom-made mechanism acting as sensor or actuator with the MEMS fabrication advanced technologies. Founding new materials such as silicon and polymers helps in miniaturization and size reduction of MEMS devices. Nano technologies and nano fabrication enable more complicated device and size reduction of MEMS and bring-in of NENS. The future of MEMS devices with the IoT and 5G bandwidth would be more involvement in our routine life.

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Fig. 8. MEMS sensors and actuators market value estimation [7].

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